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Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk

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A R T I C L E I N F O

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A B S T R A C T

Indicators used in climate change adaptation planning are largely based on estimates of national or local climate vulnerability. However, classic vulnerability indices do not consider cross-border effects and global interconnections. We attempt to reconcile this need for a broader perspective by developing a global index of exposure to transnational climate impacts, which we define as impacts that are transferred via flows between countries. The index integrates traditional climate vulnerability indicators with spatially-explicit teleconnections between specific countries and constitutes a first approximation of the distribution of such exposure globally. Our results indicate that even though climate risks emerging from within a country's borders are highly correlated with economic development and geography, the distribution of exposure to transnational climate impacts provides a much more complex picture of global vulnerabilities, which neither geography, nor economic development alone can explain sufficiently. This highlights the need to take a cross-scale and multidimensional perspective of climate risk. In order to support more robust adaptation planning, risk assessments should consider both transboundary and far-reaching teleconnected interdependencies between countries.

1. Introduction

To accomplish the ambitious targets of the Paris climate agreement, i.e. to limit global warming well below 2 degrees and to 'pursue efforts' to limit it to 1.5 degrees, countries have submitted Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate action. Recent estimates show that the INDCs collectively imply a median of 2.6–3.1 degrees warming by 2100 (Rogelj et al., 2016), with potentially severe impacts on natural and social systems (IPCC, 2014a). As a consequence, climate change adaptation will be needed in response to climate impacts (Noble et al., 2014; Ford et al., 2015). This is also stressed in the Paris agreement, which features a new reporting mechanism under the heading of 'adaptation communication' (UNFCCC, 2015). A key challenge will be to assess whether investments in adaptation options are reducing vulnerability (Berrang-Ford et al., 2011; Ford et al., 2013) and in this context it will be important to develop more rigorous methodologies to measure progress (or lack thereof) in implementing effective climate change adaptation measures (Lesnikowski et al., 2016). Presumably, a cornerstone of such methodologies will involve quantitative indicators and metrics as instruments for measuring progress in reducing vulnerability, identifying gaps and assessing effectiveness (Baker et al., 2012; Leagnavar et al., 2015; Arnott et al., 2016).

Both scholars and policy-makers are showing increasing interest in developing and using indicators to assess exposure, vulnerability, impacts and adaptation (Arnott et al., 2016). Initiatives range from overarching methods at the national level (e.g. ND-GAIN, 2015), to tailor-made approaches for development projects (e.g. Stadelmann et al., 2014; GEF, 2014) and, for instance, climate change adaptation in urban areas (e.g. Araos et al., 2016; Brandt et al., 2016; Chen et al., 2016; Tyler et al., 2016). Of specific relevance for this paper are spatial approaches to climate vulnerability where the focus is on spatial representations of factors determining vulnerability (de Sherbinin, 2014).

Here we present the first attempt to develop a global index that quantifies transnational climate risks by introducing the Transnational Climate Impacts (TCI) Index. By transnational climate impacts we mean climate impacts that reach across borders, affecting one country – and requiring adaptation there – as a result of climate change or climate-induced extreme events in another country. There is no widely accepted terminology for describing this phenomenon and a number of different terms have been proposed in the literature (e.g. spillover effects, indirect climate impacts, traded risk, international effects, systemic risks, etc.; for a review see Benzie et al., 2017). Literature on climate change vulnerability has previously acknowledged the relevance of

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Table 1
The nine index indicators along with the underlying assumptions, data sources, coverage (N representing number of countries covered and Y representing the year of the data) and method behind developing the indicators. The data was collected in 2014.

Indicator	Description: rationale and assumptions	Source	Coverage	Method
BIOPHYSICAL PATHWAY				
1. Transboundary water dependency	The proportion of water resources in a country that originates in transboundary upstream countries. The more a country relies on water from upstream transboundary rivers, the more exposed it will be to climate-related changes in transboundary river flows. For example, heavy rainfall in an upstream country can affect downstream countries by bringing floods.	FAO Aquastat	N: 187 Y: 2008–2012	Existing indicator (%)
FINANCE PATHWAY				
2. Bilateral climate-weighted foreign direct investment	The extent to which a country invests in climate vulnerable countries expressed as a function of the climate vulnerability of a country's total foreign direct investments. The larger share of GDP that is invested in climate vulnerable countries, the more exposed a country is to transnational climate impacts in that country.	UNCTAD ND-GAIN	N: 130 Y: 2008–2012	New indicator (index): Coupled data with ND-GAIN Index
3. Remittance flows	A country's dependence on the inflow of remittances. The more a country relies on remittance flows the more exposed it is to climate-related disruption in countries where migrant workers are based.	World Bank's Development Prospects Group	N: 151 Y: 2012	Existing indicator (%)
PEOPLE PATHWAY				
4. Openness to asylum	The tendency of a country to grant political asylum. Countries that grant a higher proportion of asylum applications are more likely to be affected (positively or negatively) by an increase in the number of people seeking asylum, if this turns out to be one of the consequences of climate change in other parts of the world.	UNHCR	N: 143 Y: 2012	New indicator (sum of %): Coupled data of granted political asylum with total stock of refugee population
5. Migration from climate vulnerable countries	The extent to which a country has in-migration from climate vulnerable countries. Climate change could have a significant impact on migration patterns (see Oppenheimer et al., 2014). This indicator assumes that current migration links are an indicator of potential future migration patterns. Additionally, it assumes that countries that are particularly vulnerable to (direct) climate change are more likely to experience changes in migration patterns. These are two significant assumptions that simplify the complexity of climate-migration linkages.	The World Bank's Development Prospects Group ND-GAIN	N: 183 Y: 2010 (World Bank), 2012 (ND-GAIN)	New indicator (index): Coupled data with ND-GAIN Index
TRADE PATHWAY				
6. Trade openness	A country's level of openness to trade: the sum of the country's imports and exports as a share of the country's total GDP. A country that is more open to – or engaged in – trade is more likely to be impacted by climate-related shocks and events in other (trading) countries.	UNCTAD	N: 146 Y: 2012	Existing indicator (%)
7. Cereal import dependency	The dependency of a country on imported staple foods. The more dependent a country is on food imports from abroad, the more exposed it is to climate-related disruptions in the availability, price or quality of food products.	FAO	N: 181 Y: 2007–2009	Existing indicator (%)
8. Embedded water risk	The level of consumption of embedded water that originated in water-stressed countries. The more key commodities that a country consumes that contain embedded water from water-stressed parts of the world, the more exposed it will be to climate-related change in water availability in those producer countries that are already high risk.	SEI	N: 203 Y: 2007	New indicator (index): Original modelling
GLOBAL CONTEXT				
9. KOF Globalisation Index	The level of global integration and interconnectedness of a country. The more globalised a country is, the more exposed it is to the transnational impacts of climate change.	KOF Globalisation Index	N: 191 Y: 2011	Existing indicator (index)

interconnections and globalisation (Adger et al., 2008; O'Brien et al., 2004; Moser & Hart, 2015; Challinor et al., 2017; Gotangco et al., 2017), but without any methodological advancement in terms of quantitative measurement.

As a consequence, this cross-spatial aspect of climate risk is still to a large degree ignored both in research and adaptation planning. For instance, Liverman (2016) discusses knowledge gaps and research priorities in relation to the third U.S. National Climate Assessment (NCA); she notes: "The NCA and many other regional climate impact studies generally do not take account of the global context for local climate impacts". Although the IPCC (Hewitson et al., 2014) recognises that local impacts can affect other parts of the world, there is still a lack of methodological approaches to measure this dimension spatially.

There are a few earlier examples of mostly national assessment studying transnational climate impacts, e.g. for Finland (Kankaanpää and Carter, 2007; Hildén et al., 2016), Switzerland (INFRAS et al., 2007), the United Kingdom (Foresight, 2011; PwC, 2013) and the Netherlands (Vonk et al., 2015). In the case of the UK, it was stated that impacts originating outside its jurisdiction could be "at least" as significant or even "an order of magnitude greater" than impacts within the country's borders (PwC 2013). More recently, scoping studies of the phenomenon have also started to emerge, for instance from the European Environment Agency (Lung et al., 2017).

There have also been examples of more targeted analysis of specific aspects of cascading climate change impacts, such as on the global trade system using computable general equilibrium frameworks (e.g. Constinot et al., 2016). Additionally, Wenz and Levermann (2016) use a modelling approach to assess how different countries are interconnected, and how an extreme weather event in one location - in their case a heat wave - can propagate through the global trade system and have far-reaching effects globally.

This paper provides a first rough approximation of the exposure to TCI at the country level by integrating indicator data along four transnational risk pathways through which climate risk may propagate: biophysical systems, movement of people, financial flows and international trade. The indicators assess current exposure, based on actual data. Our results show that while climate risks emerging from within a country's borders are highly correlated to different development stages (as measured by the Human Development Index, for example), exposure to transnational climate risks shows a more complex pattern with regards to rich and poor countries. Whilst a country's level of development (HDI score) is a reasonable predictor of its climate vulnerability ("poor = vulnerable"), it is not the case that countries with higher levels of development can expect to be insulated from exposure to transnational climate risk ("rich ≠ low risk") (Fig. A1). Furthermore, our results show that transnational climate risks are less spatially clustered, illustrating far-reaching entanglements of risks in an increasingly globalised world.

2. Methods and data

2.1. Index architecture

We aim for a high level of methodological transparency, recognising that impacts of this nature have hitherto not been investigated on a detailed level, and particularly not with the use of quantitative data. To facilitate transparency and in order to make our analysis reproducible, all code used for analyses is hosted at github.com/sei-international/TCI. Our approach has been to develop a framework to assist the selection of indicators, based on the extent to which they match the characteristics that we hypothesise will increase exposure at the country level. For each indicator we considered the underlying assumptions of a) why each characteristic will lead to increased exposure; and b) why the proposed indicator is a suitable measure of this characteristic; see Table 1 above.

We developed a simple and transparent framework to facilitate further research and future improvements of the prototype index that we present in this paper. The framework treats risk as potentially positive or negative, since high exposure may also equate with high opportunity in globally interconnected contexts. The framework focuses on *exposure* to impacts and does not take into account other aspects of vulnerability such as sensitivity and adaptive capacity. The nature of transnational impacts – as cross-border – implies a need to interpret the concept of exposure as something beyond the physical representation of risk, as defined by the IPCC (2014b). Instead, exposure is here understood as the characteristics of a country's profile, including the relevance and nature of links to other places (i.e. countries, markets and ecosystems), that are likely to expose it to climate-related changes in cross-border flows (as defined in our climate risk pathways framework, below). Our definition is similar to that of the IPCC in that exposure is treated as merely one component of vulnerability. High exposure heightens the climate risk (positive or negative) faced at the country level, though the realisation of this risk will be influenced by other factors, including the country's adaptive capacity. Risk is understood as potential impact.

Our framework (Fig. 1) structures transnational impacts along four risk pathways: (i) *The biophysical pathway* encompasses changing flows of ecosystem services and resources from transboundary ecosystems such as river basins, oceans and the atmosphere; (ii) *The finance pathway* represents changing capital flows resulting from climate impacts on assets held overseas; (iii) *The people pathway* involves changing flows of people between countries as a result of climate impacts, e.g. migration and tourism; and (iv) *The trade pathway* involves changing flows of goods and services via international supply chains and global markets. These four risk pathways operate over two different geographical scales; *transboundary* impacts are transmitted over borders between neighbouring countries, whereas *teleconnected* impacts result from more remote links, over greater distances. Along with indicators for the four risk pathways, we also aimed to quantify countries' relative level of globalisation, in economic, social and political terms. In the framework, this is incorporated in the global context.

The four pathways represent channels via which countries are linked by various flows. Countries are linked in one of two ways: either via systems or networks of countries, such as international markets; or; directly in bilateral exchanges, including chains of bilateral exchange, as in a modern multi-tier supply chain (see Fig. A2). Thus, the following dimensions are considered in the framework, as a basis for indicator selection:

- Dimension 1. Openness to and reliance on international flows in general; and
- Dimension 2. The climate risk of other countries to which a given country is linked.

Other dimensions that are important, but not considered in this analysis include the general variability of specific flows (e.g. price volatility of commodity X versus commodity Y) and the capacity of countries to absorb flow variability (e.g. as a function of wealth or domestic policy capacity or international influence to avoid or otherwise absorb flow variability, for example via trade policy adjustments). Assessing these aspects requires more fine-grained analysis of data at the country level, and is therefore beyond the scope of a global index such as the one presented here.

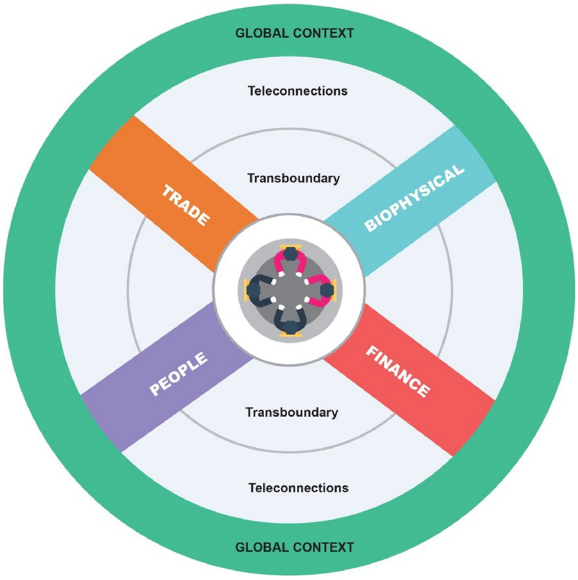


Fig. 1. The TCI framework of four climate risk pathways and the global context.

2.2. Identifying indicators for each risk pathway

As a first step, we collected a selection of indicators that represented linkages between countries for each of the four risk pathways. Subsequently, we reviewed potential indicators based on a priori characteristics associated with each pathway, and complemented this theory-based approach with expert consultations. Experts were chosen based on their experience with different aspects of indicator development in climate change and related fields. The experts were provided with a list of the proposed indicators for evaluation, which was followed by an open discussion about the representativeness of the indicators. The consultation was considered an important step to test the robustness of the assumptions behind the indicators, as well as to explore practical considerations for implementing these into a quantitative context.

Indicators were also evaluated based on the global coverage, quality and availability of data. These criteria narrowed down the initial selection of indicators, excluding those where the match between the ideal characteristics and the potential data was poor. The TCI Index requires comprehensive data on as many countries as possible to provide a global representation, but indicator selection was in some cases restricted by the availability of data with suitable global coverage, especially for many developing countries. The selected nine indicators are described in Table 1 (for detailed indicator descriptions and maps, see Benzie et al., 2016).

2.3. Index construction

Each of the nine indicators in Table 1 was classified as either belonging to Dimension 1 or Dimension 2. The trade system gives an example of the first dimension. A country's dependency on imports provides an indicator for vulnerability to climate-driven fluctuations in price and quality via the trade system in general.

Two indicators belong to Dimension 2: 'Bilateral climate-weighted foreign direct investment' (no. 2) and 'Migration from climate vulnerable countries' (no. 5). For those indicators, links to specific other countries are relevant, and they were assessed by weighting these links using data on other countries' vulnerability to direct climate change. The climate-weighted indicators were produced by joining the Notre Dame Global Adaptation (ND-GAIN, 2012) index results on climate vulnerability to bilateral data on foreign direct investment and migrations flows. There are other vulnerability indices such as the Global Climate Change Risk Index (Eckstein et al., 2018) and the World Risk Index (Welle and Birkmann, 2015), but we are not aware of any systematic analysis of strength and weaknesses of these methods in the peer reviewed literature (see de Sherbinin, 2014). We selected ND-GAIN because the index has been developed in consultation with a broad set of academics, practitioners, and private sector users (Arnott et al., 2016), and because of the transparent methodology employed by ND-GAIN and the usable format of the data.

For an indicator y in country i, the weighted indicator value y_i can be mathematically expressed as:

$$y_i = \sum_j W_{ij} * V_j \tag{1}$$

where W_{ij} is the share of y for country i in country j and V_j is the vulnerability of country j measured by the ND-GAIN index.

A majority of the indicators are non-normally distributed (Supplemental Fig. B1). Raw indicator data was standardised into deciles by the quantile method, which emphasises the relative position of values and reduces side-effects of skewed distributions. This approach facilitates map comparison, while maintaining high accuracy (Brewer and Pickle, 2002).

The global TCI Index was calculated as the mean value of the nine indicators. The index is unweighted, as we found little a priori justification for applying a higher or lower weight to some of the indicators over others, although this could be explored in further research, for example to set weights based on an expert survey.

An effort was made to include as many countries as possible in order to provide a global picture of the distribution of exposure to transnational climate impacts. However, country coverage was often patchy, even among the selected datasets. To avoid exclusion of countries with incomplete data, a threshold for index calculation was applied to only include countries with data for six or more indicators (the sensitivity of this threshold is assessed in the results section below). This resulted in a coverage of 172 countries, with data from the years 2007–2012 (Table 1).

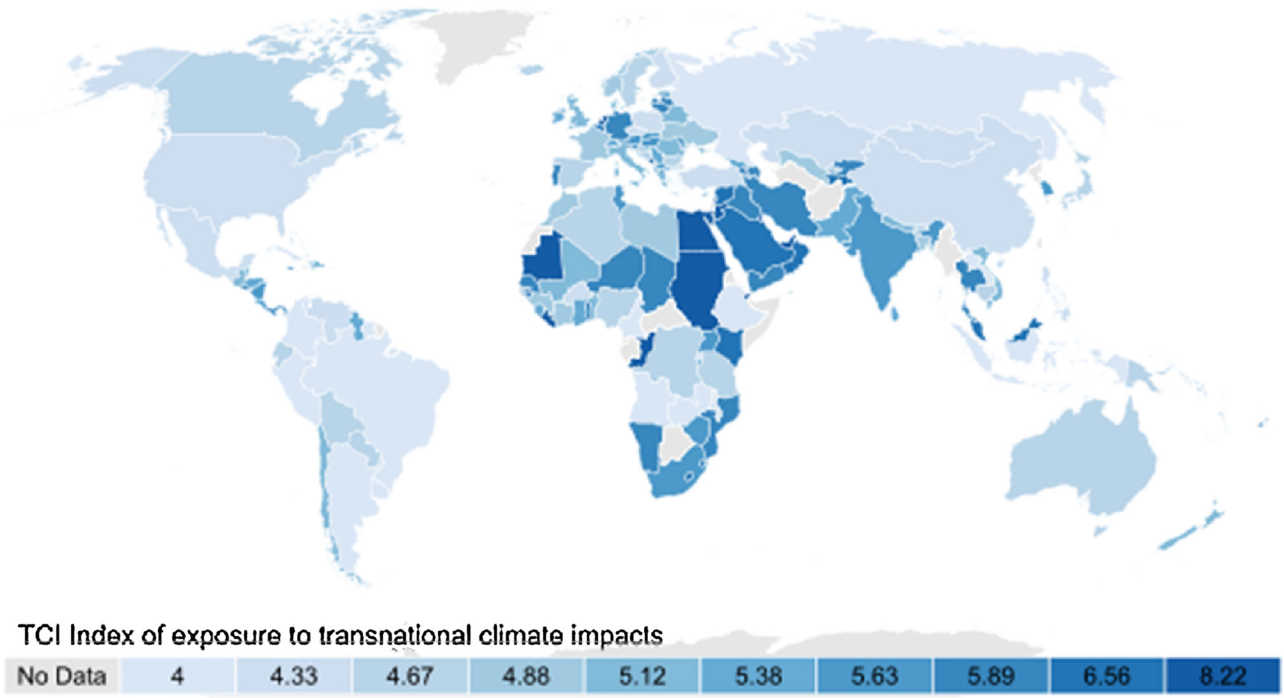
Aggregate indicators are sensitive to construction methodology and the underlying data used, and formal examination of these dependencies is critical for developing a transparent composite index (Saisana et al., 2005). To assess the robustness of TCI scores to underlying assumptions, we evaluated the influence of indicator choice, variable standardisation, and indicator uncertainty on final TCI scores.

2.4. Spatial analyses

We evaluated the spatial clustering of climate vulnerability indices among countries by calculating Moran's I, a statistical method that measures the degree to which neighbouring spatial units have similar values. High values of Moran's I indicate higher levels of global spatial clustering (autocorrelation), meaning that countries are more likely to have similar values to their neighbours.

We evaluated Moran's I for the TCI and ND-GAIN indices at multiple spatial lags, comparing index values first between neighbours, then second order neighbours (neighbours of neighbours) and so on. Analyses of autocorrelation were conducted using the function sp.correlogram in the R package spdep (Bivand and Piras, 2015) in R (R Core Team 2016).

Calculation of Moran's I is sensitive to the identification of spatial adjacency between each element in the system. We initially determined



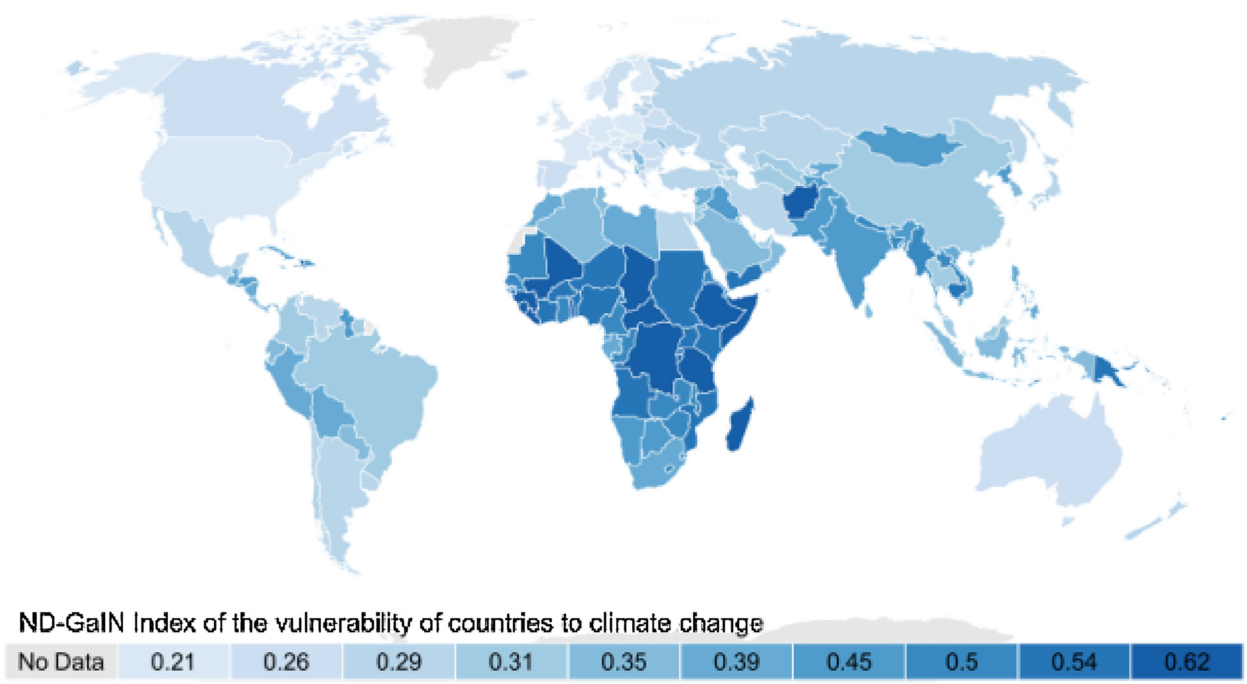


Fig. 2. TCI Index map above (for list of indicators, see Table 1) and ND-GAIN Index map below. Darker colour indicates higher exposure. For comparison, the ND-GAIN Index map was produced with new colour coding using ND-GAIN data, and the ND-GAIN data were standardised into the same number of classes as the TCI Index (10 instead of 8 classes).

spatial adjacency between countries by developing a 'line-of-sight' network between countries using delaunay triangulation between country centroids. Connections between countries were subsequently added and subtracted to represent more reasonable expectations of spatial adjacency (Supplemental Fig. B2).

3. Results and discussion

3.1. Index and indicators

Fig. 2 shows the global index of exposure to transnational climate

Table 2

Comparison of the top 30 countries on ND-GAIN and the TCI Index. The TCI Index reveals a significantly more complex and diverse distribution among countries with high exposure (with yellow for Sub-Saharan African states, orange for Middle-East and Northern African states, purple for Small Island Developing States, blue for small European states, red for South-eastern Asian states and green for Central Asia and the Caucasus states).

TCI Index

Rank	Country	Score	Region
1	Jordan	0,82	MENA
2	Bahrain	0,80	MENA
3	Mauritania	0,79	SSA
4	Lebanon	0,77	MENA
5	Kuwait	0,76	MENA
6	Congo	0,73	SSA
6	United Arab Emirates	0,73	MENA
8	Gambia	0,70	SSA
9	Liberia	0,69	SSA
9	Netherlands	0,69	EUR
11	Luxembourg	0,68	EUR
12	Montenegro	0,67	EUR
12	Djibouti	0,67	SSA
12	Egypt	0,67	MENA
15	Israel	0,66	MENA
15	Sudan	0,66	SSA
15	Belgium	0,66	EUR
15	Malaysia	0,66	SE ASIA
19	Swaziland	0,64	SSA
19	Togo	0,64	SSA
21	Kenya	0,63	SSA
21	Tajikistan	0,63	CE & C
23	Armenia	0,62	CE & C
24	Maldives	0,61	SIDS
24	Syrian Arab Republic	0,61	MENA
24	Mauritius	0,61	SIDS
27	Fiji	0,60	SIDS
27	Guinea-Bissau	0,60	SSA
27	Lesotho	0,60	SSA
27	Malta	0,60	EUR

ND-GAIN Index

Rank	Country	Score	Region
1	Somalia	0,62	SSA
2	Burundi	0,59	SSA
3	Sierra Leone	0,59	SSA
4	Afghanistan	0,58	MENA
5	Central African Republic	0,58	SSA
6	Togo	0,58	SSA
7	Liberia	0,57	SSA
8	Dem. Rep. of the Congo	0,57	SSA
9	Ethiopia	0,55	SSA
10	Guinea	0,55	SSA
11	Mali	0,54	SSA
12	Chad	0,54	SSA
13	Solomon Islands	0,54	SIDS
14	Madagascar	0,54	SIDS
15	Haiti	0,54	SIDS
16	United Republic of Tanzania	0,54	SSA
17	Guinea-Bissau	0,54	SSA
18	Timor-Leste	0,53	SIDS
19	Burkina Faso	0,53	SSA
20	Kenya	0,53	SSA
21	Niger	0,53	SSA
22	Yemen	0,53	MENA
23	Sudan	0,53	SSA
24	Uganda	0,52	SSA
25	Rwanda	0,52	SSA
26	Benin	0,52	SSA
27	Angola	0,52	SSA
28	Mozambique	0,51	SSA
29	Cote d'Ivoire	0,50	SSA
30	Nigeria	0,50	SSA

impacts (the TCI Index, upper) compared to an index of vulnerability to climate impacts inside each country's borders (ND-GAIN, lower). The distribution of TCI scores reveals new ties and interdependencies in the connective bounds between countries. European countries are ranked low in the ND-GAIN Country Index, but the TCI Index modulates this image by presenting European countries with considerable exposure to transnational climate impacts. These include mainly the Benelux countries, but also Germany, Switzerland and the Baltic states, as well as Montenegro, Malta and Portugal. In a similar vein, several of these countries also rank high in terms of global integration (Indicator 9). This may suggest a parallel relationship between global openness and exposure to transnational climate impacts.

Table 2 shows the top 30 countries for each of the indices (for full TCI index country list, see Supplemental Table B3). While only countries from Sub-Saharan Africa, MENA (Middle East and North African States) and SIDS (Small Island Developing States) are represented in the top 30 of the ND-GAIN Index, the TCI Index includes a wide variety of countries - notably smaller (e.g. the European states, Gambia, Fiji, and others), landlocked (e.g. Tajikistan, Swaziland, Armenia), highly trade dependent (e.g. Malaysia and Malta) and MENA countries (e.g. Jordan, Bahrain, Lebanon, Kuwait and United Arab Emirates – five of the highest-scoring countries). Again, this sheds light on the complexity of transnational climate impacts in both geographical and socio-economic distribution.

Altogether, small European nations account for 17% of the top 30 countries in the TCI Index. This makes Europe a significantly

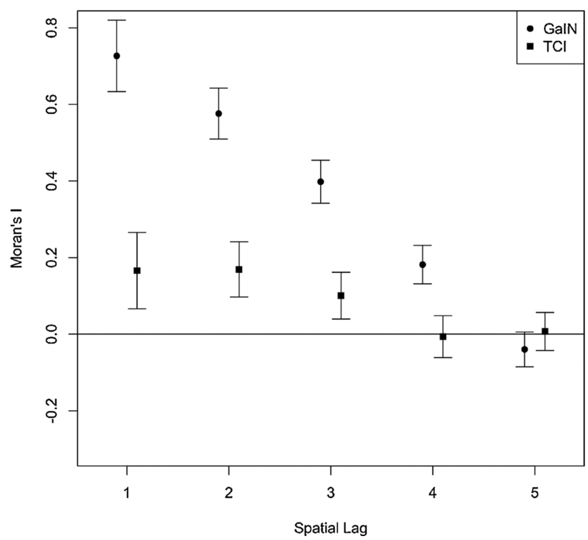


Fig. 3. Spatial Autocorrelation. Comparison of Moran's I, an index of spatial clustering, between the Transnational Climate Index and ND-GAIN index. The spatial lags represent different spatial scales, with 1 indicating nearest neighbours, 2 indicating second order neighbours (neighbours of neighbours) and so on. Climate risk is apparently much less spatially stratified when incorporating transnational perspective.

represented region, reflecting specifically the high dependency of small industrialised countries on neighbours and global systems. By contrast, no European countries feature in the top 30 of the ND-GAIN Index.

Five countries feature in the top 30 of both indices, all from sub-Saharan Africa (Togo, Liberia, Kenya, Guinea-Bissau and Sudan). Scores for sub-Saharan African countries are high in the ND-GAIN Index but varied in the TCI Index. The sub-Saharan countries with high exposure in the TCI Index however differ in which indicators are driving the high score in the aggregate results. The pathway framework can be of help in this regard by distinguishing more aggregated patterns of drivers. For example, many of the sub-Saharan African countries score high in the people pathway, even though there is a variety in what other indicators contribute to the high scores. Flows related to people dominate Sudan's high exposure result, despite the fact that the country also scores high on transboundary water dependency and the vulnerability of its foreign direct investments. Other pathway patterns can be observed in that the indicators of the trade pathway are all main drivers behind the high scores of Swaziland and Lesotho, while the latter is also highly influenced by indicators from the finance pathway.

Stronger similarities in distribution can however be observed in the patterns over North and South Americas and South and Southeast Asia. Here, countries affected by direct impacts are also exposed to transnational impacts. Still, the diverse pattern of regional results in the TCI Index remains open to explanation, for example Thailand and South Korea appear to be much more exposed to transnational impacts than they are vulnerable to direct impacts.

Overall, the index results show much less correlation between exposure and wealth, or with human development, when compared with traditional climate vulnerability indices (Fig. A1). As previously mentioned, this suggests that the factors influencing transnational climate risk are more complex and country-specific.

3.2. Sensitivity and spatial analyses

Index scores were relatively insensitive to the presence or absence of particular indicators (all rank correlations > 0.9, Supplemental Fig. B4) or number of quantiles used to determine the score (all rank correlations > 0.98). The most sensitive indicator was apparently transboundary water dependency ratio, which had the largest effect when removed from the index (Supplemental Fig. B4). This may be related to the high number of 0 values and right-skewed distribution in this dataset (Supplemental Fig. B4).

Index scores were not particularly sensitive to variation in underlying indicator values, showing minimal deviance from the original index when noise approximating ± 15% of the indicator's range was added prior to index calculation (Supplemental Fig. B4). None of the rank correlations between simulated 'noisy' and original index values differed significantly from each other, even before Bonferroni correction. (Supplemental Material B5).

The results of the spatial analysis confirm that geographical distribution of climate vulnerability for the TCI Index is more dispersed than that of ND-GAIN. Compared to the ND-GAIN index, the TCI Index exhibited significantly lower levels of spatial autocorrelation under most scales of spatial adjacency (Fig. 3).

4. Discussion

The TCI Index provides a new perspective on the complexity of exposure to climate change impacts in a globalised world. Previous indices of climate vulnerability give the impression that the vulnerability of rich (and poor) countries can be understood independently of their connections and interdependencies with other countries: as isolated entities. In contrast, the TCI Index portrays climate risk as dependent on transnational flows and interconnections as well. This multidimensional perspective on how exposure to climate risk may be experienced in the real world highlights an important research gap.

The complexity in the geographical distribution of exposure is significantly greater when considering transnational impacts as opposed to direct, local impacts. One implication is that countries cannot assume their level of exposure will be similar to that of their neighbours, warranting more detailed assessments by all countries of how transnational climate impacts might require new approaches to adaptation. This also suggests that conceptualising climate risk only in terms of biophysical processes limited to specific geographies is inadequate in a globalised context.

Although the TCI Index portrays a more complex relationship between a country's level of economic development and its exposure to climate change impacts, it remains the case that countries with lower levels of development are likely to struggle most in a changing climate. This may be exaggerated by the effect of "double exposure" to both direct and transnational impacts. Poorer countries may be least able to adapt in the face of these overlapping layers of exposure. The "climate-weighted indicators" help to assess one country's exposure to transnational impacts via other countries' exposure to direct impacts, utilising the ND-GAIN Index (i.e. country A's exposure is a function of country B's vulnerability to direct impacts). A more "complete" model of these effects could also include second- and third-order transnational risks – incorporating the exposure of the transmitting countries themselves to other countries (i.e. country A's exposure is a function of country B's exposure to transnational impacts from countries C and D, etc.). However, the processes via which risks propagate among these linked countries would require careful consideration. The complexity of such an analysis may be too great for a global indicator-based assessment to convey to users, however.

The preliminary results of the TCI Index not only reveal that no country is fully insulated from the negative impacts of climate change outside its borders, but also suggest a propensity for *cascading* risks in

the global economy as a result of climate change. A complete analysis of cascading risks is difficult to carry out in an indicator-based assessment at the global level; future efforts to do so are encouraged, but should seek to balance completeness with robustness. To this end, network-based framings and assessments of climate risk should be undertaken to explore and communicate to stakeholders and decision-makers the true character of climate risk in a globalised world, including the propensity for climate risk propagation through networks.

Our framework emphasises the properties of individual countries and the relationships between countries. One obvious reaction to this is that in many cases, trade (for instance) happens between an actor within a country and a market (Fig. A2). Global markets vary depending on the commodity; in some commodity markets, trade is relatively stable, with buyer-seller relationships that change infrequently, while in others the demand is satisfied by a market with a wide range of suppliers that are highly substitutable. This has implications for the management of climate risks via supply chains, and requires deeper and more sophisticated methodologies – and better data – in order to provide more accurate indicators of risk exposure at the national level. The area of trade-based indicators of climate risk exposure is something that deserves significant attention in future research. For example, some trade-based indicators could be argued to have dual relevance for dimension 1 and 2. Constructing these as an aggregated measurement of country-specific flow and overall dependency could be an area for future development of the index. Additionally, country-level indicator assessments of transnational climate impact exposure could look at the climate risk associated with specific commodities in specific producer countries to which that country is linked. A number of approaches combining climate impacts data with input-output data, global integrated assessment models and supply chain-specific datasets could be employed in this respect.

Due to their global interconnected nature and the complexity described above, transnational climate impacts imply a need for enhanced international cooperation on adaptation. This places climate change adaptation in a new light, where adaptation is seen more as a global collective endeavour, rather than a purely local one, which tends to dominate current assessments of climate impacts (Davis et al., 2016). This also suggests that countries with a high TCI score might choose to engage in adaptation in countries upon which they depend heavily, or to undertake measures to stabilise volatile markets. In a world of limited resources for adaptation, this also raises questions of equity, historical responsibility and self-interest as potentially competing logics for the allocation of adaptation finance internationally.

Finally, we acknowledge the general criticism of attempts to develop vulnerability indicators, e.g. Eriksen and Kelly (2007), Barnett et al. (2008) and Klein (2009). Hinkel (2011) argues that vulnerability and related concepts such as adaptive capacity and sensitivity themselves remain vague and inconsistently defined. It is therefore important to recognise that what we are trying to quantitatively assess here is a system with huge degrees of complexity, and as with all such indices, the results depend on the indicators chosen. Hence, the selection process needs to be transparent, and the ultimate choice of indicators needs to be well justified and explained. We want to make clear the limitations of the study as a decision support tool and aim to be entirely transparent about the level of analysis, including sensitivities of the index to underlying assumptions and data consistency. Despite the evidence that our index results remain relatively stable to these factors, our view is that the indicator results presented here and the global TCI Index should be used primarily to raise awareness and start discussions about the relevance of transnational climate impacts, but not yet to inform decision-making or provide a mechanism for benchmarking progress toward adaptation goals.

The index would benefit from the inclusion of new data to improve the global coverage for some indicators and improved time series data. At least as important, however, is the need to complement the quantitative analysis with qualitative aspects, capturing other – 'non-quantifiable' – dimensions of transnational climate change impacts. This could include for example informal ties between countries and historical patterns that have brought certain countries closer to each other (e.g. colonial or diplomatic links).

5. Conclusions

This paper lays out the basic structure of a framework for quantifying exposure to the transnational impacts of climate change. The goal of the framework and the TCI Index is to facilitate analysis of this emerging issue in climate change impacts and adaptation research. Summarising the conclusions of this work, the deep complexity of transnational impacts highlights the importance of a global perspective on the distribution of climate risk and measures of adaptation, which can be supported by enhanced quantitative network data. An important question, however, is whether quantification of this highly complex phenomenon is worthwhile at the global scale. Are we better off for having this index?

Systematic assessment of exposure to transnational climate risks is important for several reasons. First, it has been estimated that the costs of transnational impacts can be significant and for some countries even higher than those emerging from within the country's borders (Schenker, 2013; PwC, 2013). Second, increased awareness and more rigorous analyses of the risks associated with transnational climate impacts can support the emerging area of transnational adaptation governance (Dzebo and Stripple, 2015; Persson and Benzie, 2016). Third, it can be used as a means to inform discussion about the most effective ways to raise and allocate adaptation finance, as well as the role of international cooperation in reducing climate risks in global systems (Persson & Remmling, 2014; Benzie & Persson, 2017).

In this paper we argue that it is possible to move beyond a general recognition of measuring countries' climate risk through an isolated, local perspective; we hope the maps for each indicator and for the TCI Index provide a good starting point for such a discussion (for individual maps, see Benzie et al., 2016). We also hope to further develop the framework in the future to provide more support to decision-makers who wish to explore climate risk profiles at the national or regional level.

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Appendix A

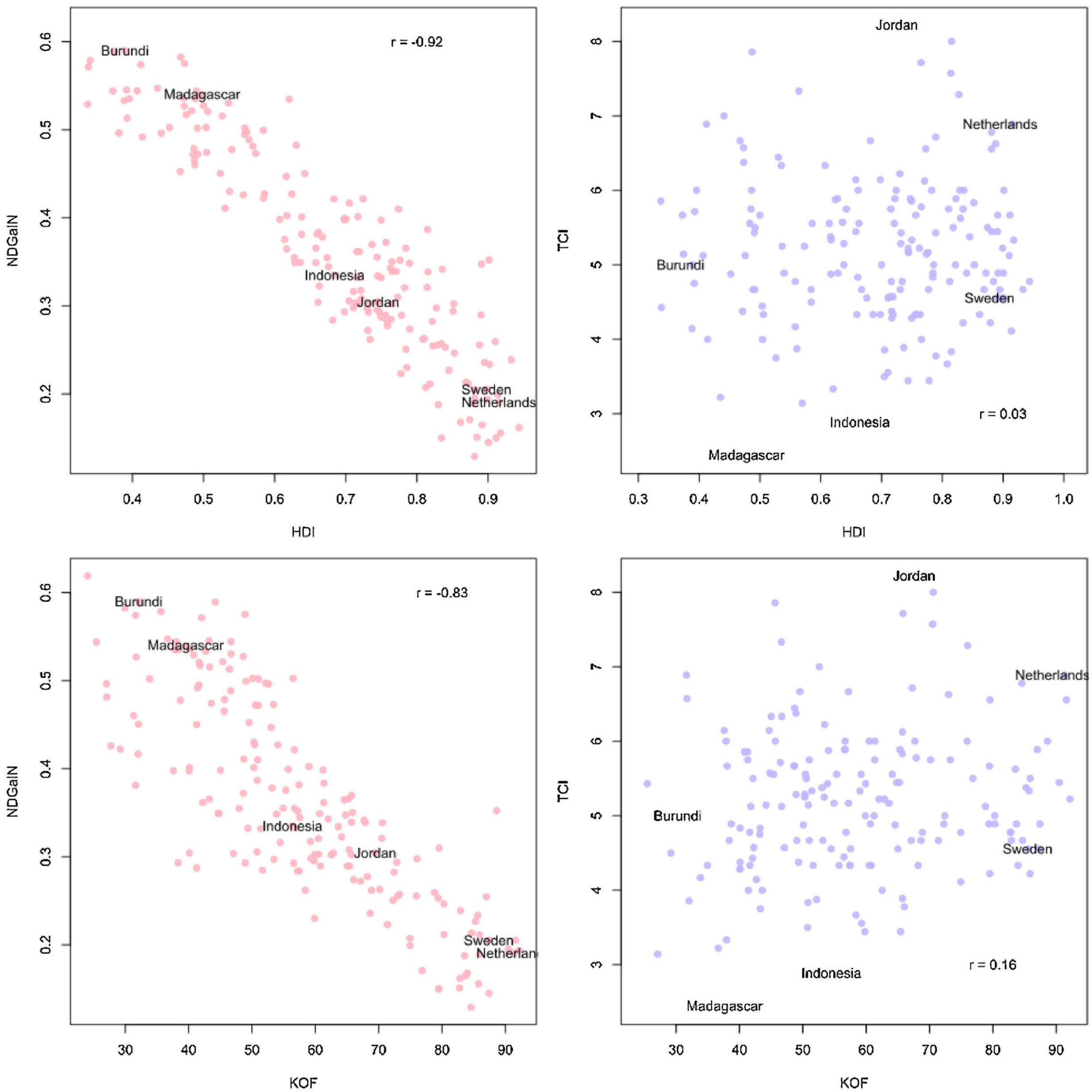

Fig. A1. Comparison of ND-GAIN and TCI.
A comparison of ND-GAIN with the Transnational Climate Index according to Human Development Index and KOF Globalisation Index. While ND-GAIN is highly correlated with HDI, TCI is uncorrelated.

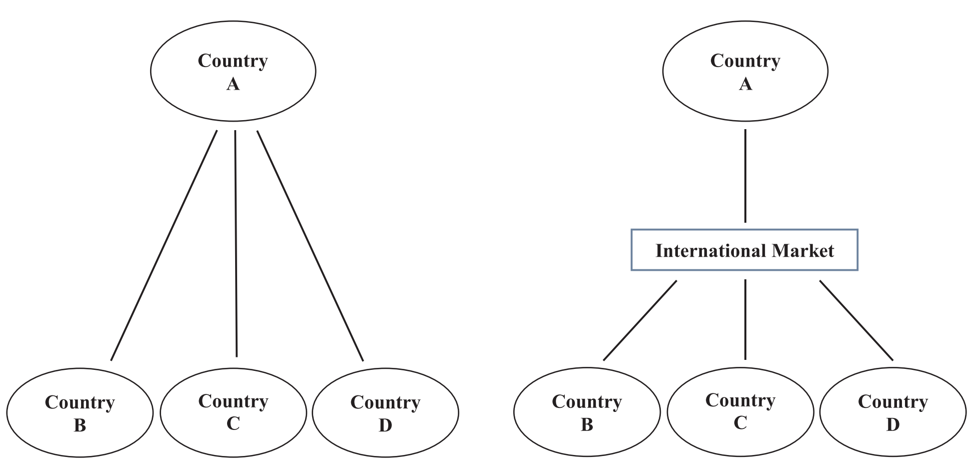

Fig. A2. Schematic illustration of country to country relationship vs. country to market relationship.

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gloenvcha.2018.04.006.

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